# High-Pressure Electrical Resistivity Measurements of $EuFe_2As_2$ Single Crystals

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**Abstract.**

High-pressure electrical resistivity measurements up to 3.0 GPa have been performed on $EuFe_2As_2$ single crystals with residual resistivity ratios $RRR = 7$ and 15. At ambient pressure, a magnetic / structural transition related to FeAs-layers is observed at $T_0 = 190$ K and 194 K for samples with $RRR = 7$ and 15, respectively. Application of hydrostatic pressure suppresses $T_0$, and then induces similar superconducting behavior in the samples with different $RRR$ values. However, the critical pressure $\sim 2.7$ GPa, where $T_0 \to 0$, for the samples with $RRR = 15$ is slightly but distinctly larger than $\sim$2.5 GPa for the samples with $RRR = 7$.

## 1. Introduction

Since the discovery of superconductivity in LaFeAs(O,F) with $T_c = 26$ K [1], a family of Fe-pnictide superconductors has attracted much attention. In particular, $A\mathrm{Fe_2As_2}$ ($A = \mathrm{Ca, Sr, Ba, Eu, etc.}$) with a tetragonal $ThCr_2Si_2$-type structure has been intensively studied because of the availability of stoichiometric single crystals with high quality. It turned out that, in Fe-pnictide compounds, the superconducting (SC) ground state could appear in accordance with the suppression of a magnetic/structural transition by doping [2]. In the phase diagrams, it is argued that the superconductivity could coexist and/or compete with the antiferromagnetism [3, 4]. However, a random potential introduced by doping could smear the intrinsic SC properties. For understanding the origin of the high-$T_c$ superconductivity with $T_c$ up to 55 K [5], it is of considerable importance to probe the systematic change of ground states using high-quality single crystals. An alternative way to tune the ground state is to apply hydrostatic pressure ($P$). For instance, recent high-$P$ ac-susceptibility and resistivity measurements have revealed that $A\mathrm{Fe_2As_2}$ ($A = \mathrm{Sr, Eu}$) exhibits $P$-induced bulk superconductivity by suppressing the magnetic/structural transition [6−10]. Meanwhile, superconductivity under hydrostatic $P$ is absent in $CaFe_2As_2$ [11−14], and remains a controversial issue in $BaFe_2As_2$ [8, 15−17]

Among the $A\mathrm{Fe_2As_2}$ series, $EuFe_2As_2$ is quite unique because the localized $Eu^{2+}$ moments order antiferromagnetically at $T_N \sim 20$ K, in addition to the magnetic/structural transition related to FeAs-layers at $T_0 \sim 190$ K [18−21]. Interestingly, the magnetic order of $Eu^{2+}$ moments

can be detected even in the SC state induced by doping or application of pressure, which could be a main reason for the novel reentrant-SC-like behavior [9, 10, 22–25].

Here, we report the results of high-$P$ electrical resistivity measurements in $EuFe_2As_2$ using newly grown single crystals with a residual resistivity ratio ($RRR$) as high as 15. At ambient $P$, the magnetic/structural transition occurs at a higher temperature of $T_0 = 194$ K, compared with 190 K for single crystals with $RRR = 7$. Consequently, it is found that the higher quality single crystal requires higher-$P$ to suppress $T_0$, and to induce the SC ground state in $EuFe_2As_2$.

## 2. Experimental Details

Single crystals of $EuFe_2As_2$ were grown by Bridgman method from a stoichiometric mixture of the constituent elements. In this study, we examined several crystals from two different batches with residual resistivity ratios $RRR = 7$ and 15, where $RRR$ is defined as $\rho_{300\mathrm{K}}/\rho_{4\mathrm{K}}$. Single crystals measured in Ref [10] were taken from a batch with $RRR = 7$. High-pressure resistivity measurements of samples with $RRR = 7$ and 15 have been performed simultaneously up to 3.0 GPa using a hybrid-type piston cylinder pressure device [26]. The resistivity was measured by the four-probe method with an ac current $I = 0.3$ mA in the $ab$ - plane. To generate hydrostatic pressure, Daphne 7474 (Idemitsu Kosan) oil, which remains in a liquid state up to 3.7 GPa at room temperature [27], was used as a pressure-transmitting medium. Samples were cooled down in Oxford $^4$He system, slowly with an average rate of 0.5 K/min. Applied pressure was estimated at 4.2 K from the resistance change of a calibrated Manganin wire [28].

## 3. Results and Discussions

Figure 1 shows the temperature ($T$) dependence of electrical resistivity scaled at 300 K ($\rho/\rho_{300\mathrm{K}}$) in $EuFe_2As_2$ single crystals with $RRR = 7$ and 15, where $RRR$ is determined as $\rho_{300\mathrm{K}}/\rho_{4\mathrm{K}}$. The measurement was performed in zero field at ambient pressure outside a pressure device with current direction $I \parallel ab$. To our knowledge, $RRR = 15$ is the largest value in $EuFe_2As_2$ single crystals [9, 21, 29]. Overall $T$-variations of the resistivity in the samples with $RRR = 7$ and 15

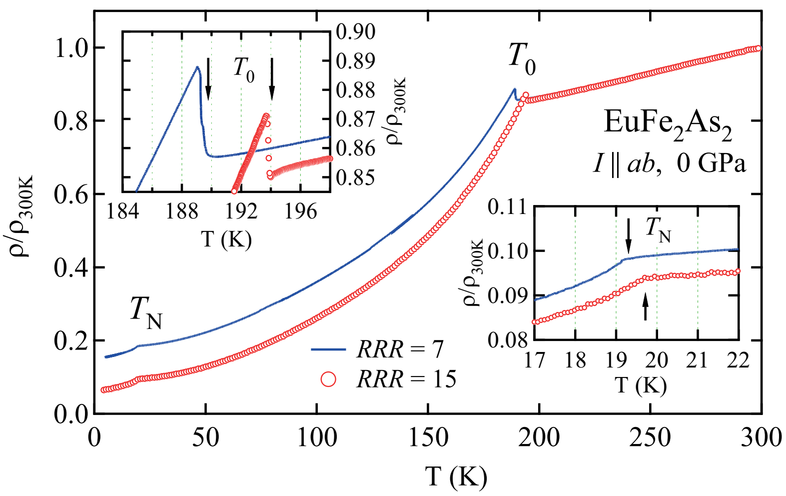


**Figure 1.** (Color online) The scaled electrical resistivity $\rho/\rho_{300\mathrm{K}}$ versus temperature in $EuFe_2As_2$ single crystals with $RRR = 7$ and 15. The measurement was carried out in zero-field at ambient pressure with the current direction $I \parallel ab$. Upper left and lower right insets represent the expanded views around $T = T_0$ and $T_N$, respectively. The data for the sample with $RRR = 7$ in the lower right inset is arbitrarily shifted in vertical direction for clarity.

are qualitatively similar to each other, and are consistent with previous results [9, 20, 21, 29]. It is worthwhile to mention that, as shown in the upper left inset, a magnetic/structural transition temperature $T_0 = 194\,\mathrm{K}$ for the sample with $RRR = 15$ is higher than $T_0 = 190\,\mathrm{K}$ for the sample with $RRR = 7$. This would be the reason why samples with $RRR = 15$ needs higher pressure ($P$) to suppress $T_0$, as will be discussed below. The Néel temperature $T_{\mathrm{N}}$ of the localized $\mathrm{Eu}^{2+}$ moments for the sample with $RRR = 15$ is slightly higher than the value for the sample with $RRR = 7$, as can be seen in the lower right inset.

Next, we turn to the pressure effect on the electrical resistivity for the samples with $RRR = 7$ (Fig. 2) and 15 (Fig. 3), which are simultaneously measured in the same pressure device. With increasing $P$, the resistivity peak related to the magnetic/structural transition is suppressed to a lower temperature in both samples as shown in Figs. 2(a) and 3(a). For the sample with $RRR = 7$, a reminiscence of the peak is clearly recognized at 2.38 GPa around 100 K, and faintly visible at 2.46 GPa around 70 K as shown in Fig. 2(a). At 2.55 GPa, there is no detectable anomaly, which implies that the critical pressure $P_{\mathrm{c}}$, where $T_0 \to 0$, may be about 2.5 GPa. For the sample with $RRR = 15$, $P_{\mathrm{c}}$ would be $\sim 2.7\,\mathrm{GPa}$ since the resistivity hump is slightly recognized at 2.69 GPa, but undetectable at 2.77 GPa as shown in Fig. 3(a). It is of interest that the resistivity follows nearly $T$-linear behavior above $T_{\mathrm{c}}$ at 2.55 and 2.77 GPa ($P \sim P_{\mathrm{c}}$) for samples with $RRR = 7$ and 15, respectively, as guided by a dashed line. A similar $T$-variation of resistivity was also reported in several optimally-doped Fe-pnictide superconductors [4, 30–32]. For the sample with $RRR = 7$, a resistivity upturn and a small maximum, as indicated by an arrow in Figs. 2(b), in the broad SC transition below 31 K are observed at $P = 2.38\,\mathrm{GPa}$ ($< P_{\mathrm{c}}$). It suggests that the superconductivity is suppressed by the magnetic order of the $\mathrm{Eu}^{2+}$ moments; consequently, reentrant-SC-like behavior appears. A similar behavior is also slightly seen for the sample with $RRR = 15$ (Figs. 3(b)), but more smeared out. At $P > P_{\mathrm{c}}$, resistivity exhibits sharp SC transitions to zero-resistivity with $T_{\mathrm{c}} \sim 30\,\mathrm{K}$ for both samples. With increasing $P$, the SC

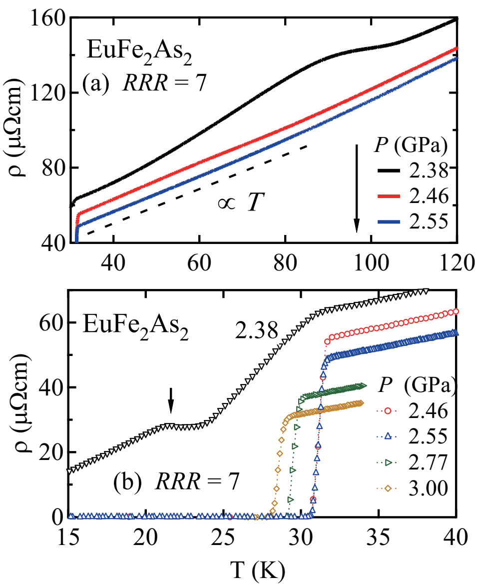


**Figure 2.** $\rho$ vs $T$ of a $\mathrm{EuFe_2As_2}$ single crystal ($RRR = 7$) up to 3.0 GPa in the temperature ranges (a) $30 - 120\,\mathrm{K}$ and (b) $15 - 40\,\mathrm{K}$. An arrow in (b) indicates an anomaly attributed to $T_{\mathrm{N}}$

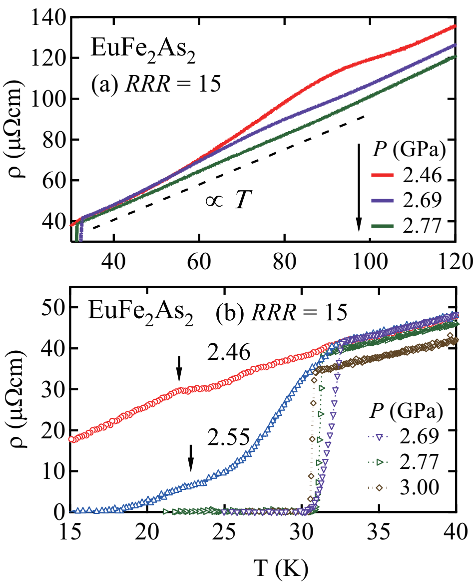


**Figure 3.** $\rho$ vs $T$ of a $\mathrm{EuFe_2As_2}$ single crystal ($RRR = 15$) up to 3.0 GPa in the temperature ranges (a) $30 - 120\,\mathrm{K}$ and (b) $15 - 40\,\mathrm{K}$. Arrows in (b) indicate anomalies attributed to $T_{\mathrm{N}}$.

transitions persist up to 3.00 GPa although the $T_c$ continuously decreases. Thus, the $P$-variation of the resistive behavior between the samples with different quality is qualitatively similar to each other, and is consistent with the previous result [10]. However, $P_c \sim 2.7$ GPa for the sample with $RRR = 15$ is slightly but distinctly larger than $\sim 2.5$ GPa for the sample with $RRR = 7$, which may be as a consequence of the larger value of $T_0$ for the higher-quality sample at ambient-$P$. We have repeated similar high-$P$ resistivity measurements using several single crystals, and confirmed that the observed difference in the magnitude of $T_0$ and $P_c$ between the samples with $RRR = 7$ and 15 is beyond the error of the pressure estimation ($\pm 2$ - $3 \times 10^{-2}$ GPa) [28]. Another meaningful issue, which probably relates to the sample quality, is the width of a SC transition $\Delta T_c$. The minimum values of $\Delta T_c$ are 1 K and 0.8 K for samples with $RRR = 7$ and 15, respectively. These facts suggest that the higher-quality single crystals have larger values of $T_0$ and $P_c$ as well as a sharper SC transition in $EuFe_2As_2$.

Until now, there has been no report concerning the quantum oscillation in $EuFe_2As_2$, despite the importance for understanding the Fermi surface topology and mass renormalization. In fact, we have already tried de Haas-van Alphen (dHvA) measurements of $EuFe_2As_2$ using the samples with $RRR = 7$ at 0.6 K with fields up to 35 T, but could not detect any dHvA oscillation. Given that quantum oscillations were successfully detected in $SrFe_2As_2$ ($RRR \sim 8$) [33] and $BaFe_2As_2$($RRR = 10$) [34], it is worthwhile to perform the dHvA measurement of $EuFe_2As_2$ using the newly grown single crystals with $RRR = 15$.

## 4. Conclusions

We have performed high-pressure electrical resistivity measurements up to 3.0 GPa in $EuFe_2As_2$ single crystals with $RRR = 7$ and 15. At ambient pressure, a magnetic/structural transition occurred at $T_0 = 190$ K and 194 K for the samples with $RRR = 7$ and 15, respectively. Although $P$-induced superconductivity was confirmed in the samples with different $RRR$ values, the critical pressure $P_c \sim 2.7$ GPa for the samples with $RRR = 15$ was slightly but distinctly larger than $\sim 2.5$ GPa for the samples with $RRR = 7$.

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